

Radio Variability of the Sagittarius A* due to an Orbiting Star

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Abstract. Recently, unprecedentedly accurate data on the orbital motion of stars in the vicinity of the Sagittarius A* have been available. Such information can be used not only to constrain the mass of the supermassive black hole (SMBH) in the Galactic center but also to study the source of the radio emission. Two major competing explanations of the radio spectrum of the Sagittarius A* are based on two different models, that is, hot accretion disk and jet. Hence, independent observational constraints are required to resolve related issues. It has been suggested that a star passing-by a hot accretion disk may cool the hot accretion disk by Comptonization and consequently cause the radio flux variation. We explore the possibility of using the observational data of the star S2, currently closest to the Galactic center, to distinguish physical models for the radio emission of the Sagittarius A*, by applying the stellar cooling model to the Sagittarius A* with the orbital parameters derived from the observation. The relative difference in the electron temperature due to the stellar cooling from the star S2 at the pericenter is a few parts of a thousand and the consequent relative radio luminosity difference is order of 10^{-4} . Therefore, one could possibly expect to observe the radio flux variation with a periodic or quasi-periodic modulation in the frequency range at $\nu \lesssim 100\text{MHz}$ if the radiatively inefficient hot accretion flows are indeed responsible for the radio emission, contrary to the case of a jet. According to our findings, even though no periodic radio flux variations have been reported up to date a radiatively inefficient hot accretion disk model cannot be conclusively ruled out. This is simply because the current available sensitivity is insufficient and because the energy bands they have studied are too high to observe the effect of the star S2 even if it indeed interacts with the hot disk.

Key words. accretion, accretion disks – Galaxy:center – galaxies:active – black hole physics

1. Introduction

The compact radio source in our Galactic center Sagittarius A* is widely believed to be associated with an accreting supermassive black hole (SMBH) whose mass is $\sim 10^6 M_\odot$ (Eckart & Genzel 1997; Ghez et al. 1998; Melia & Falcke 2001; Eckart 2002). A number of models for the observed radio spectrum are essentially based on an accretion process as quasars and active galactic nuclei are powered by accreting SMBHs (e.g., Rees 1984). Though the existence of the SMBH at the Galactic center and its role seem unanimously accepted, the details of the accretion process and/or the nature of the central inner part of the accretion flow remain unsettled. For instance, even the recent *Chandra* observation of X-ray flare by Baganoff et al. (2001) have been explained by physically quite dif-

ferent models of the Sagittarius A* (Markoff et al. 2001; Liu & Melia 2002; Yuan, Markoff, & Falcke 2002).

Lower radio luminosities from Sagittarius A* can be reasonably well explained by the radiatively inefficient accretion flow, such as, advection-dominated accretion flows (Narayan, Yi, & Mahadevan 1995). The radiative luminosity of the advection-dominated accretion flows (ADAFs) is much less than that of the standard thin disk (Shakura & Sunyaev 1973). The ADAFs have a low luminosity since most of the energy in the flows is stored in hot ions and advected into the central black hole due to the low efficiency of heat transfer from ions to electrons (Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994). The electron temperature is very high, and thus the electrons are relativistic.

Several models have been further introduced to account for the detailed spectrum of the Sagittarius A*. Other versions of the radiatively inefficient accretion flow,

for instance, are accretion flows with significant macroscopic convection (Narayan, Igumenshchev & Abramowicz 2000; Quataert & Gruzinov 2000a), so called convection-dominated accretion flows (CDAF), those with mass loss due to outflows from the accretion flow (Blandford & Begelman 1999; Turolla & Dullemond 2000), advection-dominated inflow-outflow solutions (ADIOS). A truncated disk with a radio jet has been also proposed (Falcke & Biermann 1999; Falcke & Markoff 2000; Beckert & Falcke 2002; Yuan, Markoff, & Falcke 2002). They have both virtues and drawbacks in explaining the spectrum in details, implying that the spectral energy distribution alone is probably insufficient to sort out models. Hence, the independent observations resolving the central part are required to settle down related issues. One of examples is the polarization observation. Constraints by the linear/circular polarization measurements seem quite robust (Agol 2000; Quataert & Gruzinov 2000b; Melia, Liu, & Coker 2000; Aitken et al. 2000; Bower et al. 2003). The measured polarizations provide information on the emitting region, the mass accretion rate, the nature of the accretion flows, the physical process of the radio emission, and so on. Another example which has been of great interests for observers is flux variations (Baganoff et al. 2001; Duschl & Lesch 1994; Eckart 2002; Hornstein et al. 2002; Goldwurm et al. 2003; Zhao, Bower, & Goss 2001; Zhao et al. 2003). The short time-scale variation is of course important since it may provide the information on the physical change in the inner part of the accretion disk (e.g., Mushotzky, Done, & Pounds 1993). On the other hand, the long time-scale variation in the very low frequency band can also provide the useful information on the central engine of the source like the Sagittarius A*.

This paper is motivated by the recent observational report on the proper motion of stars close to the Sagittarius A* (Schödel et al. 2002; Gezari et al. 2002; Ghez et al. 2003). Stellar proper motion data covered by an interval from 1992 to 2002 allows to determine orbital accelerations for some of the most central stars of the Galaxy, thus the mass of the Sagittarius A*. The observations covering both pericenter and apocenter passages show that the star S2, currently closest star to the Sagittarius A*, is on a bound, highly elliptical Keplerian orbit around the SMBH, with an orbital period of ~ 15 years, a pericenter distance of only 124 AU, or ~ 2000 Schwarzschild radius, the eccentricity of 0.87. As mentioned above, it will be interesting to consider a way to constrain the central source of the Sagittarius A* using this kind of observation. We explore the possibility of using the observational data to distinguish physical models for the radio emission of the Sagittarius A*. A similar attempts to this paper have been already made in the sense that the same observational data are used to test putative accretion disk theories (Nayakshin & Sunyaev 2003; Cuadra, Nayakshin, & Sunyaev 2003). Using the three dimensional orbit of the star S2 the latter authors concluded that there could exist no optically thick and geometrically thin disk near the Sagittarius A* or the cool disk must have a large inner

edge since otherwise it should have exhibited observational signatures over the period of the observation campaign. In this paper we apply the stellar cooling model suggested by Chang (2001) to the particular case of the Sagittarius A* by recalculating with the orbital parameters derived from the observation.

2. Stellar Interaction with ADAF

A hot accretion disk is believed to exist in low luminosity AGNs and dormant galaxies, such as, our own Galaxy (Narayan, Yi, & Mahadevan 1995; Narayan et al. 1998; Ho 1999). If there is an accretion disk around the SMBH, several processes may occur due to the interaction of a flying-by star and the accretion disk around the SMBH (Syer, Clarke, & Rees 1991; Hall, Clarke, & Pringle 1996), without mentioning the tidal disruption events (Cannizzo, Lee, & Goodman 1990; Rees 1988, 1990; Menou & Quataert 2001; Komossa 2002; Choi et al. 2002). A more interesting phenomenon can be observed particularly when the accretion disk is relativistically hot. Stellar interactions with such a hot accretion flow around the SMBH play an intriguing role in that an flying-by star may cool the hot accretion disk as a result of Comptonization (Chang 2001). One of observable signatures of a flying-by star in the hot accretion disk, e.g., the ADAFs is the decrease of the electron temperature and subsequently the radio flux of the hot accretion disk. In the followings it is briefly summarized what happens when a bright star encounters a hot accretion disk.

Firstly, when a star passes through the accretion disk around the SMBH the dynamical friction causes the viscous heating. The power is given by $P = F_{\text{df}} v_{\text{rel}}$, where F_{df} is the drag force and v_{rel} is the relative velocity of the star with respect to the background gas. The drag force F_{df} on a star with mass M_* moving through a uniform gas density ρ with the relative velocity v_{rel} can be estimated as

$$F_{\text{df}} = -4\pi I \left(\frac{GM_*}{v_{\text{rel}}} \right)^2 \rho, \quad (1)$$

where the negative sign indicates that the force acts in the opposite direction of the star, G is the gravitational constant (Ostriker 1999; Narayan 2000). The coefficient I depends on the Mach number, $\mathcal{M} \equiv v_{\text{rel}}/c_s$, where c_s is the sound speed of the medium. In the limit of a slow moving $\mathcal{M} \ll 1$, $I_{\text{subsonic}} \rightarrow \mathcal{M}^3/3$, so that the resulting F_{df} is proportional to the relative speed of the star. In the limit of a fast moving $\mathcal{M} \gg 1$, $I_{\text{supersonic}} \rightarrow \ln(v_{\text{rel}}t/r_{\text{min}})$, where r_{min} is the effective size of the regime where the gravity of the star dominates. We take the supersonic estimate of I , as it gives an upper limit on the heating due to the drag force, which makes the total cooling estimate obtained here a lower limit of the stellar cooling effect.

Secondly, on the other hand, the stellar emission may cool the gaseous medium. In the ADAFs a star and its motion may enhance the cooling by bremsstrahlung and Comptonization processes. The gas density in front of the

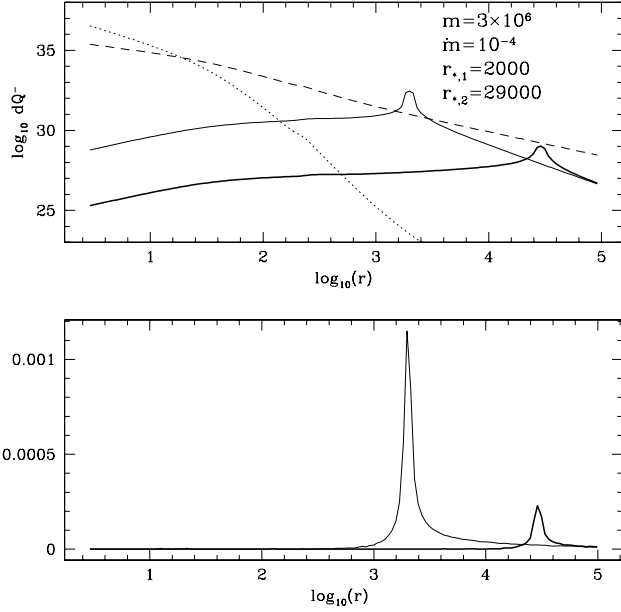


Fig. 1. Upper panel: The volume integrated cooling rate over the spherical shell due to various cooling mechanisms are shown as a function of r in log scales. The dQ^- 's are in ergs s^{-1} . Lower panel: The relative electron temperature differences are shown as a function of r . The relative electron temperature difference is defined as $(T_0 - T_*)/T_0$, where T_0 is the electron temperature of the case without the stellar cooling. The thin and thick solid curves represent the cases when the cooling star is at $r \sim 2000$ and $r \sim 29000$, respectively. The dotted curve and the dashed curve represent volume-integrated cooling rate due to synchrotron cooling and bremsstrahlung cooling, respectively.

star may be increased as the motion of the star may compress the gas. The bremsstrahlung cooling rate per volume is increased as the density increases proportionally to the square of the density (Stepney & Guilbert 1983). Comptonization is also possible because the electrons in the ADAFs are relativistic since radiation emitted by the star is an important source of soft photons. The stellar cooling rate due to Comptonization becomes relatively important than those due to other processes of accretion disk cooling when the mass accretion rate becomes small.

3. Radio Variation due to Stellar Cooling

Making the simplest assumption of an optically thin and quasi-spherical hot accretion disk, we examine observational features due to the hot accretion flow present around the Sagittarius A* through its interaction with the closely flying-by star, that is, S2. Using the orbital parameters and the observed positions of the currently closest star S2 (Schödel et al. 2002; Ghez et al. 2003), we are able to calculate the radio flux variation which could have been observed with a similar period of the orbital period of the star. We adopt the following dimensionless variables

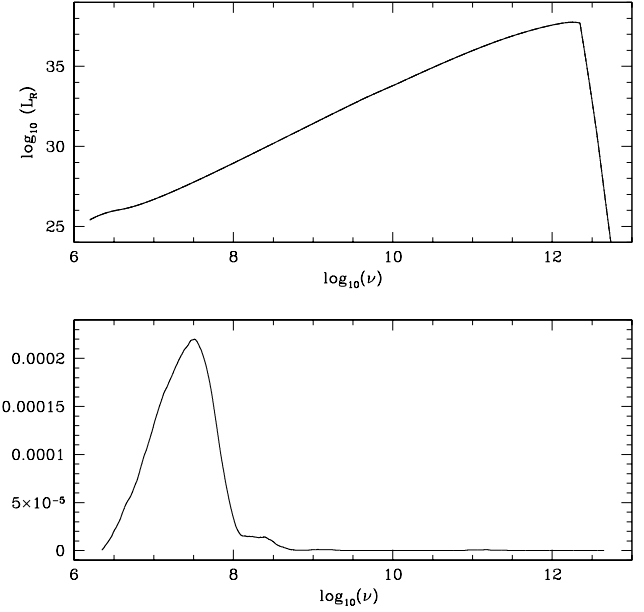


Fig. 2. Upper panel: The radio spectrum of the ADAFs is shown. We show the radio spectra of the ADAFs without the stellar cooling by the solid curve, and with the stellar cooling at the pericenter by the dotted curve and at the apocenter by the dashed curve. Note that all the curves are indistinguishable at this scale. The luminosity in ergs s^{-1} and the frequency in Hz are shown in the log scale. Lower panel: The relative difference of the radio spectrum at two different epochs is shown.

throughout the paper : mass of the SMBH $m = M/M_\odot$; radius from the SMBH $r = R/R_g$, where $R_g = 2GM/c^2 = 2.95 \times 10^5 m \text{ cm}$; and mass accretion rate $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$, where $\dot{M}_{\text{Edd}} = L_{\text{Edd}}/\eta_{\text{eff}}c^2 = 1.39 \times 10^{18} m \text{ g s}^{-1}$ (the Eddington accretion rate assuming $\eta_{\text{eff}} = 0.1$). We model the accreting gas as a two-temperature plasma. As typical values in a model for the ADAFs parameters are taken to be $r_{\text{min}} = 3$, $r_{\text{max}} = 10^5$, $\alpha = 0.3$, $\beta = 0.5$, and $\delta = 0.0$ (see, e.g., Narayan & Yi 1995; Quataert & Narayan 1999).

Provided that the background gas environment is described by the ADAF model, the volume-integrated cooling rate due to stellar emission $dQ_{*,C}^-$ over the spherical shell at r can be obtained. We plot $dQ_{*,C}^-$ with other volume-integrated cooling rates as a function of r in Figure 1. We adopt the bolometric luminosity of S2 as that of an O8 dwarf (Ghez et al. 2003). The dotted curve and the dashed curve represent volume-integrated cooling rate due to synchrotron cooling $dQ_{\text{sync}}^- + dQ_{\text{sync},C}^-$ and bremsstrahlung cooling $dQ_{\text{br}}^- + dQ_{\text{br},C}^-$. The thin and thick continuous curve represent $dQ_{*,C}^-$ when the S2 star is at pericenter and at apocenter, respectively. These volume-integrated cooling rates are subject to the mass accretion rate to the central SMBH. The synchrotron cooling dQ_{sync}^- and bremsstrahlung cooling dQ_{br}^- are reduced as the mass accretion rate is decreased. The stellar cooling rate be-

haves similarly. However, its relative contribution becomes more significant compared with others as the mass accretion rate is small. We adopt the mass accretion rate is $\dot{m} = 10^{-4}$ (Quataert, Narayan, & Reid 1999; Quataert & Gruzinov 2000b), which corresponds to the favored accretion rate estimation from the observation when the ADAF model is assumed. We also show the relative differences in the electron temperature as a function of r when the cooling star is at $r \sim 2000$ and $r \sim 29000$ denoted by the thin and thick solid curves, respectively. The relative electron temperature difference is defined as $(T_0 - T_*)/T_0$, where T_0 is the electron temperature of the case without the stellar cooling. The electron temperature is again averaged over the volume of the shell. As shown in the plot, for a given SMBH mass and the mass accretion rate the suppression of the temperature due to the stellar cooling becomes less significant as the cooling star is at farther away from the central SMBH.

In Figure 2, we show the radio spectrum of the ADAFs in the upper panel and the relative difference of the radio spectrum due to the stellar coolings at two different epochs. The relative difference of radio spectrum has been given for two different epochs, that is, when the star is at pericenter and at apocenter. Since the dominant effects on the spectrum is due to the inner parts of the ADAFs, the stellar cooling at farther from the SMBH changes the spectrum less significantly. The suppression of the radio spectrum due to the stellar cooling is the greatest at the frequency corresponding to the position where the star cools the accretion disk (see Mahadevan 1997). It can be understood by the fact that the synchrotron radio emission of the ADAFs at each frequency is closely related to a specific radius. For instance, the emission at higher frequencies originates at smaller radii, or closer to the central supermassive black hole. As shown in the lower panel Comptonization of stellar soft photons from the star at $r \gtrsim 10^3$ affects the radio spectrum at $\nu \lesssim 100\text{MHz}$.

4. Summary and Discussions

When a star like S2 interacts with the hot accretion disk such as the ADAFs in the Galactic center one would expect many interesting effects. One of observable signature of a stellar encounter with the hot accretion disk such as the ADAFs is the depression of the radio flux due to the stellar cooling, whose variation could show periodic or quasi-periodic modulation. We have attempted to calculate what one may actually expect using observed parameters of the currently closest star S2. The relative electron temperature difference is a few parts of a thousand without and with the stellar cooling in the case when the star S2 is near at the pericenter. Subsequently the radio spectrum shows the suppression of the radio spectrum due to stellar cooling which is the greatest at the frequency at $\nu \lesssim 100\text{MHz}$ for stellar soft photons from the star at $r \gtrsim 10^3$. The relative radio luminosity difference without and with the stellar cooling is small, order of 10^{-4} . Bower et al. (2002) have reported multiepoch, multifre-

quency observations of the Sagittarius A*, from 1981 to 1998, of which data have been taken at 1.4, 4.8, 8.4, and 15 GHz bands. They have found no periodic radio flux variation with a period ~ 15 years, which is naturally expected from the presence of a hot disk. We suggest that this observation cannot be used yet to distinguish two competing models, i.e., hot accretion disk and jets. That is, even though no periodic radio flux variations have been found in the observations a radiatively inefficient hot accretion disk model cannot be conclusively ruled out. This is simply because the currently available sensitivity is insufficient and because the energy bands they have studied are too high to observe the effect of the star S2 even if it indeed interacts with the hot disk.

We tentatively conclude that even the currently closest pass of the star S2 is insufficiently close enough to meaningfully constrain the nature of the Sagittarius A*. Yet again, we would like to emphasize that currently available data are out of range which the star S2 would have affected. Quantitative implications may be subject to parameters we adopt for the background accretion flow model and the physical parameters of the encountering star. One may employ another version of the radiatively inefficient accretion flow, for instance, CDAFs. Changing the background from ADAFs to CDAFs has insignificant modification in our conclusions since the convection in the hot accretion flows alters the very inner part of the accretion flows and therefore the spectrum at high frequency range, $\nu \gtrsim 1\text{GHz}$ (see Ball, Narayan, & Quataert 2001). The mass loss in ADIOS also causes a significant effect only at higher frequency range than we have interests. We, however, point out that a long monitoring of radio flux and the stellar proper motion observation are still worthwhile to be pursued since a hypothetical star orbiting a very eccentric orbit might exist near at its apocenter where it spends most of the orbital period and yet more closely pass by the Sagittarius A* than the star S2. If that happens we may observe the radio flux variation at $\nu \gtrsim 1\text{GHz}$, where one should be more careful in choosing the background accretion flow model. One may also attempt to monitor LLAGNs, which are believed to host the ADAFs or their variations (Ho 1999). For an accreting SMBH with a lower mass accretion rate and more closely flying-by star may exhibit their existence.

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